A SUSPENDED SEDIMENT BUDGET OF THE YICHANG–WUHAN REACH OF

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ABSTRACT. The amount of the sediment deposition in the Yichan–Wuhan reach of the middle Yangtze River (also known as Changjiang River) has been determined using the concept of sediment budget at the channel-reach scale. The fill–scour processes of the middle Yangtze River were studied during the period 1956–1997 in response to the variation in sediment load and flow inputs. The results show that 13.3% of the net input of sediment was deposited in the studied river reach. Since 1956, the output sediment load of the studied reach increased with time to 1981, followed by a decline. The increase in output before 1981 can be related to the man-made bend neck-cutoff which caused a decrease in the sediment load diverted through the 'three outfalls' (i.e. the three distributaries from the Yangtze main stem to the Dongting Lake) and increased the sediment-carrying capacity of the river. Thereby, the river could transport more sediment to the outlet of the studied river reach. The decrease in the sediment load output after 1984 was directly due to the decreased sediment load at Yichang station. Multiple regression equations have been established to assess the contributions of influencing factors to the variation in sediment deposition amount in the studied river reach.

Key words: sediment deposition, channel sediment budget, scour-fill behaviour, environmental change, Yangtze River

Introduction

The Yangtze River is a large river for both China and the world; its hydrological and geomorphological processes are of concern to scientists both in China and worldwide, and have been the objective of much research (e.g. Shen 1965; Institute of Geography, Chinese Academy of Sciences and Yangtze River Institute of Water Conservancy and Hydropower Research 1985). In the past 30 years, owing to the influence of climate change and human activities, the sediment load and water discharge of the Yangtze River and its tributaries have changed (Beardsley *et al*. 1985; Xu 2000; Yin and Li 2001; X.Q. Chen *et al*. 2001; Z.Y. Chen *et al*. 2001; Zhang and Wen 2002; Yang *et al*. 2002). The construction of Three Gorges Dam will change the temporal and spatial distribution of sediment load and river flow to a great extent and thus alter the sediment and water inputs to the middle and lower reaches of the Yangtze River below Yichang. The middle and lower Yangtze is basically an alluvial river, being formed in alluvium carried by the river and deposited in the past, apart from some local bank controls such as bedrock hills. Hence, when the sediment and flow inputs are changed, the river will adjust itself through scour and fill to a re-established equilibrium. Some researchers have studied the scour and fill behaviours of the middle and lower Yangtze River. Li and coworkers (Li and Ni 1998; Li *et al*. 2000b) studied the influence of sediment transport and flood protection on sediment deposition, and the relationship between sediment deposition and water regulation by the Dongting Lake (Li *et al*. 2000a). Lu (1996) studied the variation in flow and sediment load diverted by the outfalls. Xiong (1996) studied the channel changes of the lower Jingjiang River, a local name for the Ouchi–Chenglingji reach of the Yangtze River. However, sufficient attention has not yet been paid to the river's process of scour–fill in response to the sediment and flow input and output.

Much research has been done in the field of river sedimentation and channel adjustment (e.g. Coleman 1969; Hooke 1995; Xu 1997, 2002a, b; Benedetti 2003). Erosion, transport and deposition of sediment are basic geomorphic processes in a fluvial system (Schumm 1977). They can be linked by the concept of sediment budget at basin scales (Di-

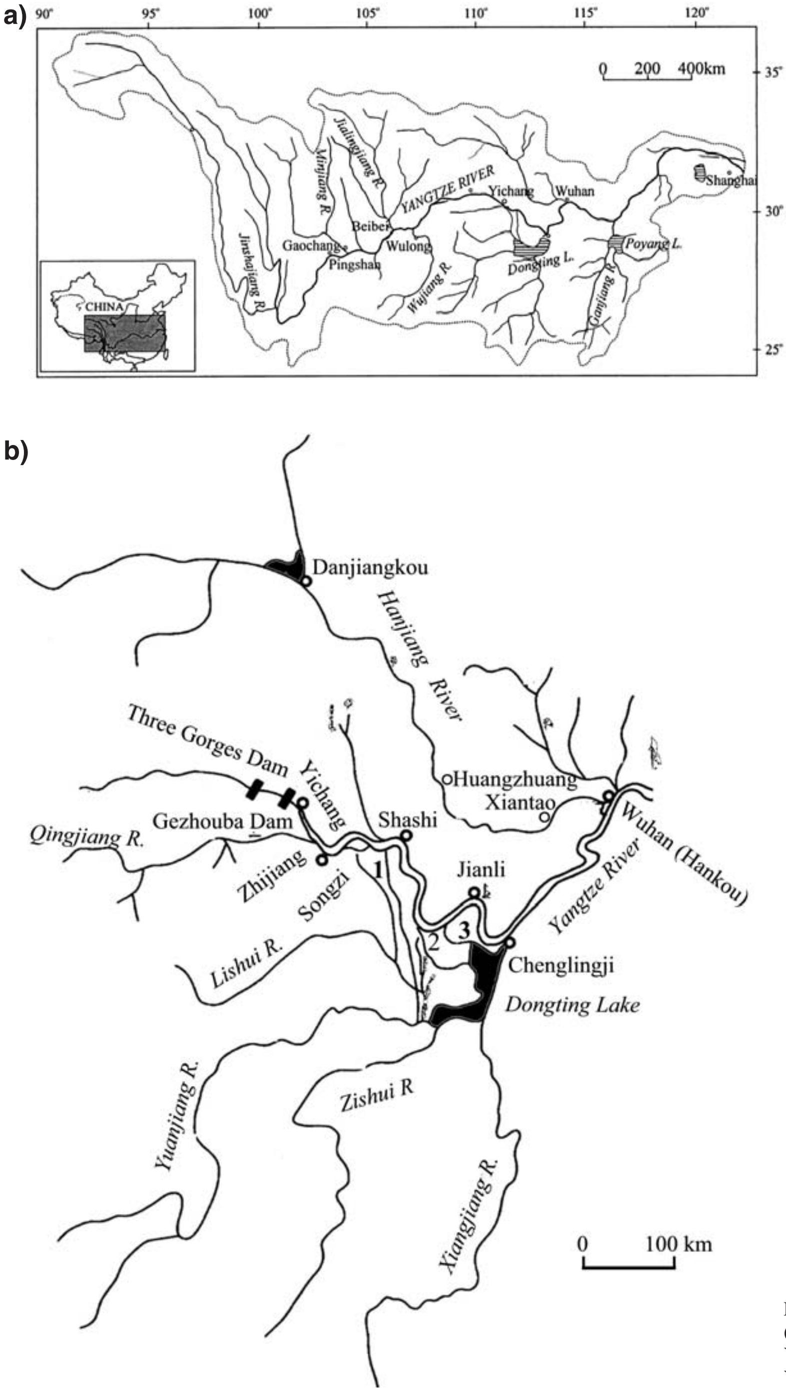

Fig.1a. The Yangtze River basin (after Wang *et al*. 2005). b. The Yichang-Wuhan river reach of the Yangtze River basin

etrich and Dunne 1978; Trimble 1981), i.e. sediment yield of a fluvial system equals the sum of erosion minus the sum of sediment deposition into storage within the drainage basin. Sediment transport may be divided into two parts: the sediment transport on hillslopes and that in channels. Thus, the concept of sediment budget can be applied to hillslopes and the river channel separately. Using the concept of sediment budget on channel scales, the quantities of scour and fill for a given channel reach can be determined. This opens a way to obtain data for a study of river response to environmental changes because the amount of sediment deposition at river-reach scales can be calculated using data of sediment loads collected from hydrometric stations controlling the flow and sediment input and output of the given river reach. It is usually expensive and time-consuming to collect data of sediment deposition along a large river like the Yangtze by high-resolution channel cross-section survey.

Applying the channel sediment budget approach, sediment delivery processes of the Yellow River have been studied by Xu (2003). In the present study, this approach will be further applied to the Yangtze River, to elucidate its scour–fill behaviour in response to the sediment and flow inputs.

Outlines of the studied river reach, data source and method

Yichang, above which the drainage area of the Yangtze River is 100.5 million km^2, is the dividing point between the upper and middle reaches of the Yangtze River (Fig. 1a) and controls the river flow and sediment load from the upper to the middle Yangtze River. The mean annual water discharge is 13 883 m^3/s at Yichang station, and suspended sediment load is 500.94 million tonnes. Below Yichang, the river leaves mountainous areas and enters a vast alluvial plain known as the Middle and Lower Yangtze River Plain. The Yichang–Wuhan reach may be divided into four subreaches according to channel morphology (Fig. 1b). (1) The subreach from Yichang to Zhijiang is a single channel, locally confined by terraces and bedrock hills. In this subreach, the transition from a gravel bed to a sand bed occurs. (2) The subreach from Zhijiang to Ouchi, known as upper Jingjiang, is 168 km in length, and is a meandering channel, with some alluvial islands appearing occasionally. (3) The subreach from Ouchi to Chenglingji, known as lower Jingjing, is 170 km in length, and is a typical meandering channel. Natural bend neck-cutoffs have occurred frequently. (4) The subreach from Chenglingji to Wuhan has and 'island' channel pattern, i.e. some stable mid-channel alluvial islands are well developed; their surface height is roughly the same as the floodplain, and they divide the channel to form a multithread one.

The Lower Jingjiang is the characterized by the frequent occurrence of natural bend neck-cutoffs in the past. In 1967 and 1969, two man-made bend neck-cutoffs were created, at Zhongzhouzi and Shangchewan, to improve the navigation channel (Fig. 2a). In 1972, a natural cutoff occurred at Shatanzi. Due to these three cutoffs, the length of the river was reduced by 78 km, and the channel sinuosity of the lower Jingjiang decreased from 3.0 to 2.0. These cutoffs significantly increased the local channel slope, and therefore enhanced the river's sediment-carrying capacity, resulting in degradation below the point of cutoff. The lowering of bed due to scour may cause backward erosion upstream from the cutoff point, also resulting in bed degradation. The increased sediment load due to upstream degradation may cause sediment deposition downstream from the scoured reach. Thus, the occurrence of cutoffs induced strong channel adjustment, which may have had some influence on the channel sediment budget in the Yichang–Wuhan reach.

Due to the coupling between the Yangtze River and Dongting Lake (Fig. 2a), the channel sediment budget of the Yichang–Wuhan reach is complicated. Between the mainstem of the upper and lower Jingjiang reaches and the Dongting Lake, a channel network of distributaries developed in the past, and thus the mainstem of Jingjiang, the distributary channels and Dongting Lake constitute a coupled system, known as the 'river–lake coupled system'. This system has a great influence on the channel sediment budget. Part of the sediment load from the upper Yangtze River is diverted through the distributaries to Dongting Lake and deposited there, significantly reducing the sediment load of the mainstem downstream.

High artificial levees have been built along both banks of the Jingjiang River, for flood protection. To release the flood of the mainstem to the distributaries in case an abnormal flood occurs, some 'gaps' were left on the levee. In the past, there were many such 'gaps', but by 1954 only four remained; these are known as the 'four outfalls', Songzhi, Taiping, Ouchi and Tiaoxian. In 1959, a sluice gate was built at Tiaoxian, and in 1970 the sluice gate was closed, since then there have been only three

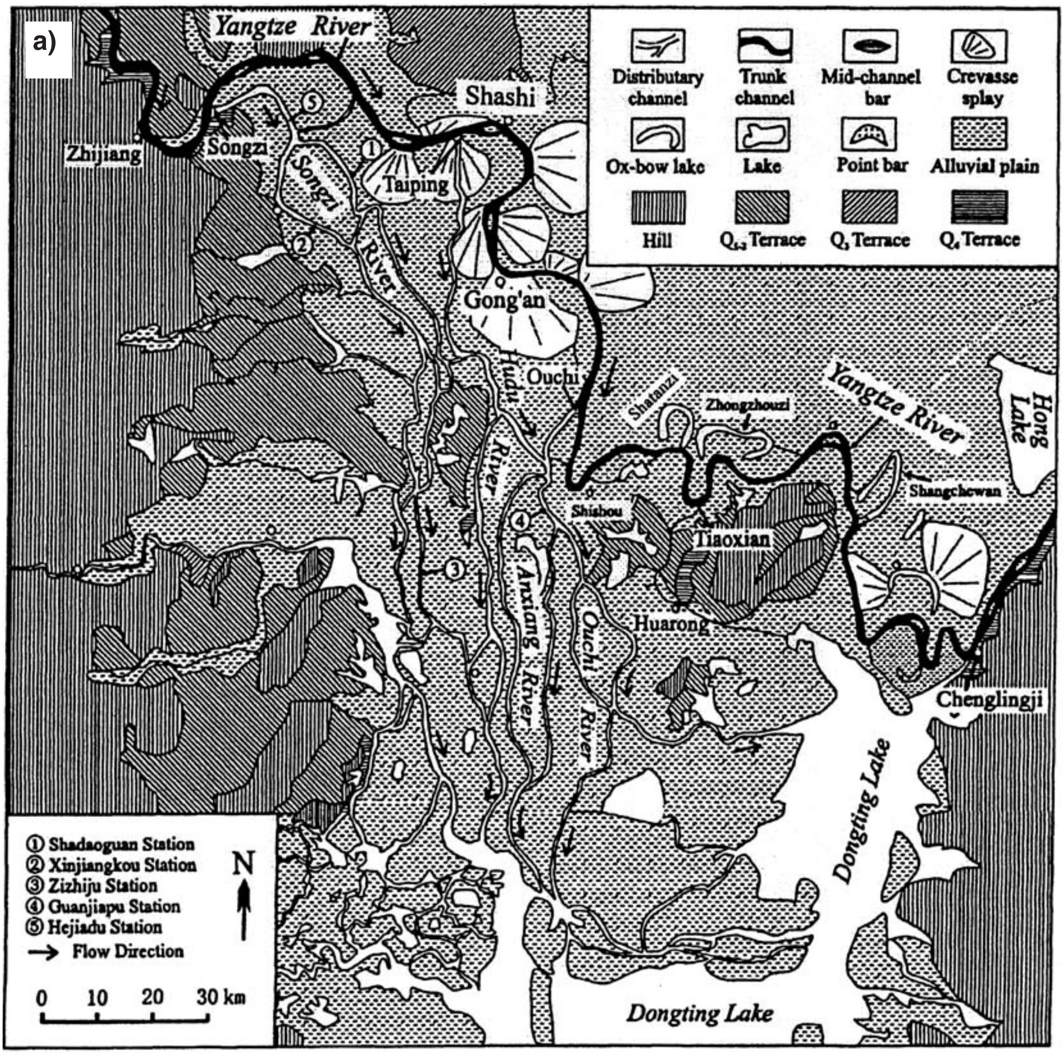

Fig. 2a. Coupling between the Yangtze River and the Dongting Lake (after Wang *et al*. 2005). b. Input and output of the Yichjang–Hankou reach of Yangtze River

outfalls. There is a waterway linking Dongting Lake and the Yangtze River. The water of the lake, including the water from the rivers emptying to the lake and from the three outfalls, may flow to the Yangtze River mainstem through this waterway which is gauged at Chenglingji hydrometric station.

The Hanjiang River, a major tributary of the Yangtze River, joins the mainstem near Hankou (Fig. 1). The flow and sediment load of the Hanjiang to the Yangtze mainstem is measured at Xiantao station. As long-term data are not available at Xiantao station, the flow and sediment loads measured at Huangzhuang station are used to represent the loads to the Yangtze mainstem. Hankou station is just in Wuhan on the Yangtze and is the end of the Yichang–Wuhan reach; the flow and sediment loads measured at this station are the outputs of flow and sediment load of the studied reach. Another tributary, the Qingjiang River, joins the mainstem above Zhijiang, but the flow and sediment load from the Qingjiang River to the Yangtze River account for only 1.7% and 0.4%, respectively, of the loads of the Yangtze measured at Yichang station (Li and Ni 1998), and thus they are not taken into account. The sediment input and output for the Yichang–Wuhan reach are generalized as shown in Fig. 2b.

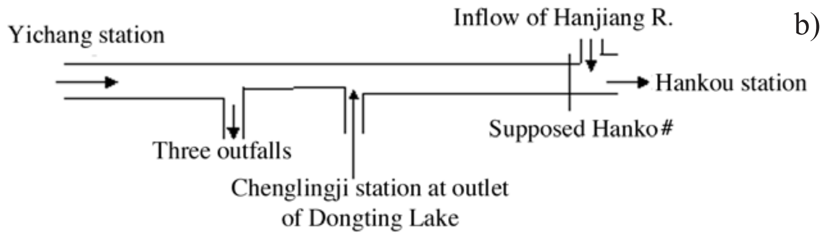

Fig. 2. Continued

In terms of sediment budget concept, the annual amount of sediment scour or fill can be determined as following the sediment deposition of the Yichang–Wuhan reach = total sediment input – total sediment output, minus total sediment output:

$$S_{\text{dep,Y-H}} = (Q_{\text{s,Yichang}} + Q_{\text{s,Chenglingji}} + Q_{\text{s,Huangzhuang}}) - (Q_{\text{s,3outfalls}} + Q_{\text{s,Hankou}}) \quad (1)$$

where $S_{\text{dep,Y-H}}$ is the sediment deposition of the Yichang–Wuhan reach, $Q_{\text{s,Yichang}}$ is annual suspended sediment load at Yichang station, representing the sediment input to the studied river reach from the upstream drainage basin of the upper Yangtze River. $Q_{\text{s,Hankou}}$ is annual suspended sediment load at Hankou station, representing the sediment load output from the studied river reach. $Q_{\text{s,Chenglingji}}$ is annual suspended sediment load at Chenglingji station, representing sediment load from the Dongting Lake to the Yangtze River. $Q_{\text{s,Huangzhuang}}$ is mean annual suspended load at Huangzhuang station, representing the sediment inflow from the Hanjiang River to the river reach. $Q_{\text{s,3outfalls}}$ is the sum of annual suspended loads measured at the three outfalls, i.e. Songzi, Taiping and Ouchi distributaries, representing the sediment load outflow from the Yangtze main stem to the Dongting Lake (Fig. 1b). The unit for all the variables is 10^4 tonnes/year.

As the confluence between the Hanjiang and Yangtze rivers is just above Hankou station, the sediment load inflow from the Hanjiang River immediately flows out of the studied river reach and therefore basically has no influence on sediment deposition in the studied river reach. Thus, for simplicity, we introduce a supposed control point just above the Hanjiang–Yangtze confluence, which is called Hankou$^{\#}$ (Fig. 2b), as the end of the Yichang–Wuhan reach. The sediment load from the Hanjiang River may then be excluded when considering the channel sediment deposition in the Yichang–Wuhan reach. The sediment load at Hankou$^{\#}$ can be calculated as the sediment load at Hankou station on the Yangtze River minus that at Huangzhuang station on the Hanjiang River. Thus, the equation of sediment balance may be rewritten as follows:

$$S_{\text{dep,Y-H\#}} = (Q_{\text{s,Yichang}} + Q_{\text{s,Chenglingji}}) - (Q_{\text{s,3outfalls}} + Q_{\text{s,Hankou\#}}) \quad (2)$$

where $S_{\text{dep,Y-H\#}}$ is sediment deposition of the Yichang–Hankou$^{\#}$ river reach:

$$Q_{\text{s,Hankou\#}} = Q_{\text{s,Hankou}} - Q_{\text{s,Huangzhuang}}.$$

The annual sediment deposition of Yichang–Hankou$^{\#}$ river reach has been calculated using Equation 2. All the data involved are from the relevant hydrometric stations, as mentioned above. It should be pointed out that the sediment budget established in this study is only for suspended sediment load, with bed-load ignored, because bed-load data are not available, as is the case for most rivers in the world. The studied river reach has a sandy bed material. According to some incomplete measurements made at Yichang station, the ratio of bed-load to suspended load is only 1–2% (Institute of Geography, Chinese Academy of Sciences and Yangtze River Institute of Water Conservancy and Hydro-power Research 1985).

Regular hydrometric measurements of water stage, discharge, suspended sediment concentration and grain size, and suspended sediment load are conducted by the engineers and workers of the relevant hydrometric stations, following national standards issued by the Hydrological Bureau, Ministry of Water Conservancy and Electric Power (e.g. 1962, 1975, 1992). Discharge is calculated using the velocity–area method based on daily velocity measurements at the cross-section. Cross-section measurement of suspended sediment transport rate is conducted more than 30 times a year. Each time suspended sediment samples are taken at more than 25 verticals, usually five or six points for each vertical. Then the cross-section average **suspended sediment concentration (*SSC*)** is calculated. Single *SSC* sediment sample is taken once a day, but

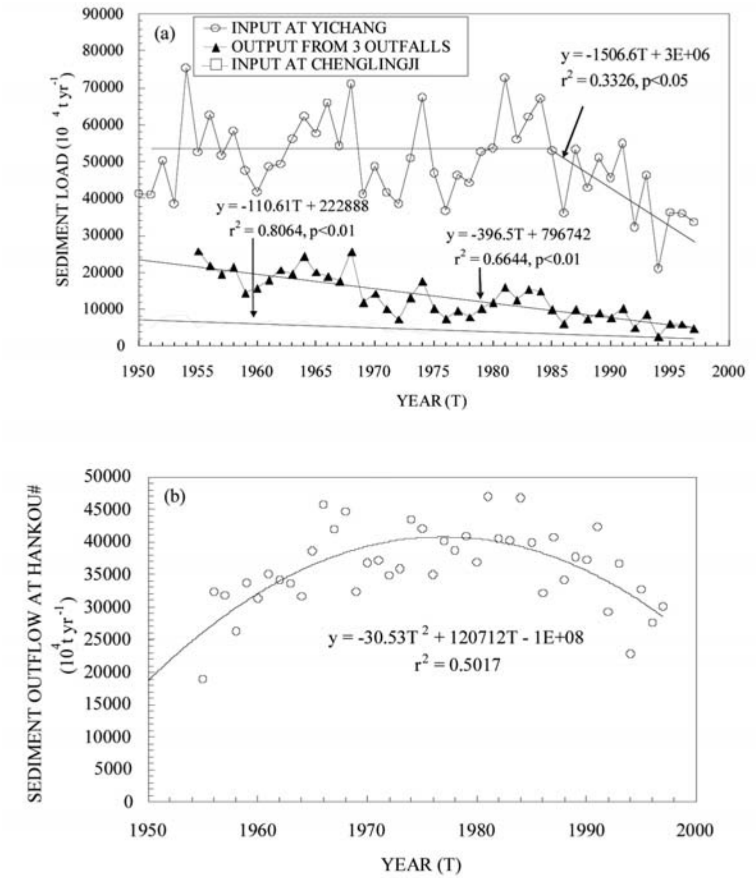

Fig. 3. Temporal variations in four components of the channel sediment budget of the Yichang–Hankou# reach. Equations refer to the indicated trend lines. (a) Inflow sediment at Yichang station ($Q_{s,\,Yichang}$), outflow sediment through the three outfalls ($Q_{s,\,3outfalls}$) and inflow sediment from the Dongting Lake ($Q_{s,\,Chenglingji}$). (b) Sediment outflow at Hankou#

five to seven times per day during floods. Using the previously established relationship between cross-section-averaged *SSC* and single-sample *SSC*, the daily *SSC* single-sample is converted to daily cross-section-averaged *SSC*. Daily **suspended sediment load (*SSL)*** is calculated as daily water discharge multiplied by daily *SSC*. Summing the daily ***SSL*** gives the annual *SSL*.

After annual sediment deposition is determined, it is further related to the variables of river flow and sediment load of the studied river reach using empirical statistical approaches, to elucidate the response of sediment deposition to the changing river flow and sediment load input.

The following indices are introduced to describe the river flow and sediment load inputs: (1) annual river flow ($Q_{w,Yichang}$) and suspended load ($Q_{s,Yichang}$) at Yichang station; (2) annual flow ($Q_{w,3outfalls}$) and suspended load ($Q_{s,3outfalls}$) flowing to Dongting Lake through the three distributaries, represented by the sum of river flow or suspended load at the stations on Songzi River, Hudu River, Anxianghe and Ouchi Rivers (see Fig. 2b); (3) annual river flow ($Q_{w,Chenglingji}$) and suspended load ($Q_{s,Chenglingji}$) at Chenglingji station, representing the features of the water and sediment flowing from Dongting Lake to the Yangtze mainstem.

Variations in the components of channel sediment budget

As mentioned above, the channel sediment budget of the Yichang–Hankou# reach includes four components: inflow sediment at Yichang station ($Q_{s,Yichang}$), outflow sediment through the three outfalls ($Q_{s,3outfalls}$), inflow sediment from Dongting Lake ($Q_{s,Chenglingji}$) and outflow sediment at Hankou#. The temporal variations in these four components have been plotted in Fig. 3.

Figure 3a shows that the temporal variation in annual suspended load at Yichang station may be divided into two stages. From 1951 to 1984, although

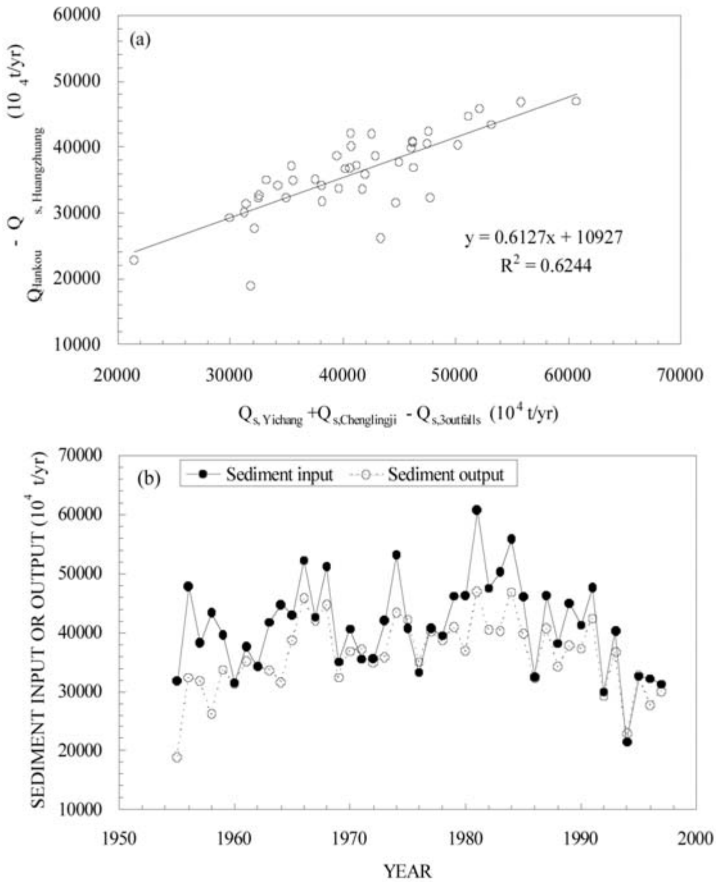

Fig. 4. Relationship between the total net sediment input ($Q_{s,Yichang} - Q_{s,3outfalls} + Q_{s,Chenlingji}$) and the sediment output ($Q_{s,Yichang} - Q_{s,Huangzhuang}$) of the studied river reach (a) and their temporal variations (b)

there were some fluctuations, no overall trend can be seen. However, from 1985 to 1997, a clear decreasing trend appeared. This decreasing trend may be related to the implementation of soil and water conservation measures and the building of large numbers of reservoirs and checkdams since the 1980s, as a result of which the sediment supply to the Yangtze River has been reduced to some degree. Figure 3a also shows a clear decreasing trend in annual outflow of sediment ($Q_{s,3outfalls}$, in 10^4 t/year) through the three outfalls, as indicated by the regression equation.

The decrease in the diversion of sediment through distributaries to Dongting Lake can be related to human impacts, especially to the man-made bend neck-cutoffs in the lower Jingjiang River in 1967 and 1969. The resultant strong scour lowered the elevation of the river bed of the Yangtze mainstem near the three outfalls, which means a relative rise of the river bed of the distributaries. As a result, less floodwater could flow out of the mainstem to Dongting Lake.

The annual sediment amount from Dongting Lake to the Yangtze mainstem represented by the sediment load at Chenglingji station is small (Fig. 3a), accounting for only 8.2% of the annual sediment load at Yichang station. The variation in annual sediment load at Chenglingji station ($Q_{s,Chenglingji}$, in 10^4 t/year) with time (T, in years) shows a clear decreasing trend.

The temporal variation in the total net sediment input to the studied river reach may be (expressed as) $Q_{s,Yichang} + Q_{s,Chenglingji} - Q_{s,3outfalls}$. The temporal variation in the sediment output at the end of the studied river reach, Hankou# (expressed as $Q_{s,Hankou} - Q_{s,Huangzhuang}$), can be seen in Fig. 3b. The relationship between the total net sediment input and the sediment output of the studied river reach has been plotted in Fig. 4a, which indicates a close positive correlation. A comparison of the temporal variations in total net sediment input and the sediment output of the studied river reach is given in Fig. 4b, which shows clearly the scour and fill in the reach on an annual ba-

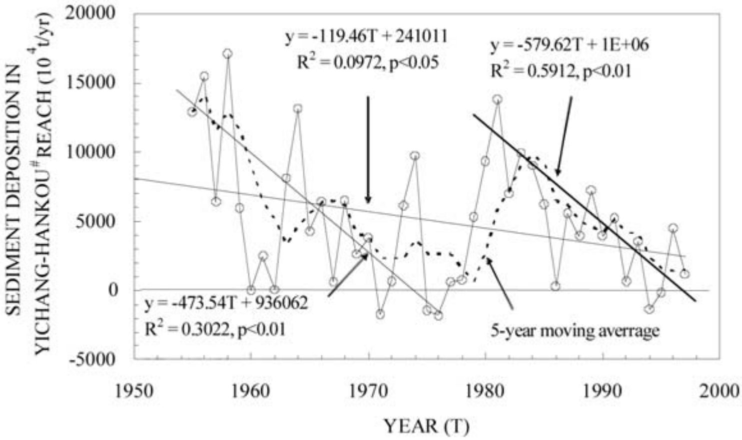

Fig. 5. Temporal variation in annual sediment deposition in the Yichang–Hankou# river reach

sis. The distance between each pair of points for each year indicates the magnitude of fill (if the point of sediment input is higher) or scour (if the point of sediment input is lower). Thus, it can be seen that from 1955 to the 1960s and 1970s, the fill decreased. In the early 1980s, the fill became significant, and then declined.

The input of sediment for the studied river reach is highly positively correlated with the output of sediment, indicating that the studied river reach has a function of 'more input, more output'. The sum of sediment input during the period from 1955 to 1997 was calculated as $1\,898\,465 \times 10^4$ t, and the total sediment output was $1\,646\,628 \times 10^4$ t; thus, 13.3% of the sediment input was deposited in the studied river reach. The sedimentation mainly occurred in the reach from Chengjingji to Hankou, and the amount of sedimentation in the reach from Yichang to Chenglingji was negligibly small, at least after the scouring induced by bend neck-cutoffs in this reach (Hydrological Bureau of the Changjiang River Commission 2002a). Based on 1:10 000 river channel maps surveyed in 1981 and 1998 for the Chenglingji–Hankou reach, sediment deposition was estimated by superposing the maps in 1998 on those in 1981. The results show that 172 million m^3 of sediment was deposited in the channel below bankfull stage, and 473.6 million m^3 on the floodplain (Hydrological Bureau of the Changjiang River Commission 2002b). Thus, only 36.3% of the sediment was deposited in the channel below bankfull stage. As a result, the river bed elevation of the Chenglingji–Hankou reach rose to some degree, and sediment bars enlarged.

Figure 3b shows that the sediment output ($Q_{s,Hankou}$#, in 10^4 t/year) of the Yichang–Hankou# river reach increased with time (T, in years) to a peak, followed by a decline. This variation can be fitted by a parabolic equation (see Fig. 3b).

The temporal variation in sediment deposition ($S_{dep,Y\text{-}H\#}$) in the Yichang–Hankou# river reach has been plotted in Fig. 5, where a fitted line of five-year moving average is shown. It can be seen that from 1955 to 1976 a decreasing trend appeared, and from 1976 to 1981 a sharply increasing trend appeared. Afterwards, the sediment deposition declined. From 1981 to 1984, sediment load at Yichang station was high (see Fig. 3a). Thus, $S_{dep,Y\text{-}H\#}$ was also high. Afterwards, sediment input of the studied reach decreased, resulting in a decreasing tread in $S_{dep,Y\text{-}H\#}$. The period from 1955 to 1997 may be divided into two subperiods, from 1955 to 1979 and from 1980 to 1997. The regression lines for all points and for those in the period 1980–1997 are given respectively. For all points, the correlation coefficient is $r = -0.3117$, significant at a level of <0.05, indicating that the sediment deposition rate has a mild overall decreasing trend. The correlation coefficient for the period 1980–1997 is $r = -0.7689$, much more significant than that for all points, indicating a strong decreasing trend since 1980. This may be related to the decrease in the net sediment input, especially with the decrease in the sediment load at Yichang station. It is worth noting that the variation in the sediment deposition in the period 1954–1979 is complicated and the increase in the net sediment input and in ($Q_{s,Yichang} - Q_{s,3outfalls} + Q_{s,Chenglingji}$), did not always result in an increase in sediment deposition in the studied river reach. It seems that this may be attributed to the strong channel adjustment following the three bend neck-cutoffs that occurred in 1967, 1968 and 1972.

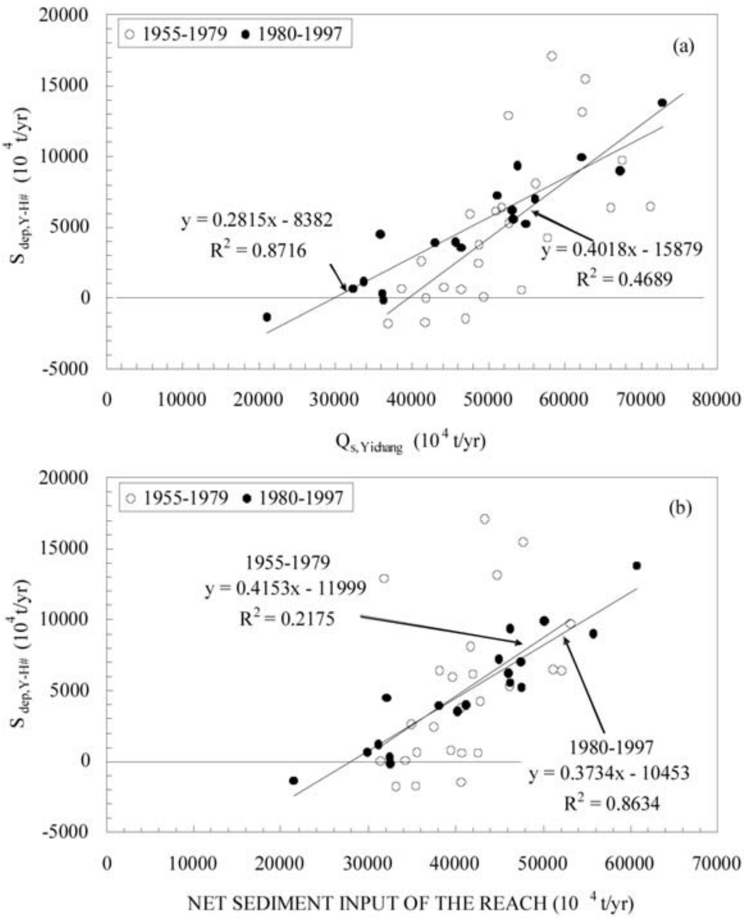

Fig. 6. (a) Annual amount of sediment deposition ($S_{dep,Y\text{-}H\#}$) in the Yichang–Hankou# river plotted against the annual sediment load at Yichang station ($Q_{s,Yichang}$). (b) Net sediment input ($Q_{s,Yichang}$ – $Q_{s,3outfalls} + Q_{s,Chenlingji}$) of the studied river reach

Relationship between sediment deposition in the studied river reach and the river flow and sediment inputs

The annual sediment deposition ($S_{dep,Y\text{-}H\#}$) in the Yichang–Hankou# river reach has been plotted against the annual sediment load at Yichang station and the net sediment input ($Q_{s,net}$) of the studied river reach expressed as the index ($Q_{s,Yichang}$ – $Q_{s,3outfalls} + Q_{s,Chenlingji}$) in Fig. 6a and b respectively. Although the points are scattered, the squared correlation coefficients for the above two plots are $r^2 = 0.54$ and $r^2 = 0.40$, both much larger than the critical squared regression coefficient significant at level of <0.01, $r_c^2 = 0.1546$. As pointed out above, due to the difference in sediment input and in channel adjustment, two periods, 1955–1979 and 1980–1997, can be identified. Thus, the points in the two periods are distinguished by different symbols.

Based on data from 1980 to 1997, a regression equation between annual amount of sediment deposition ($S_{dep,\ Y\text{-}H\#}$ in 10^4 t/year) in the Yichang–Hankou# river reach and annual suspended load ($Q_{s,Ychang}$) at Yichang station has been established as follows:

$$S_{dep,Y\text{-}H\#} = 0.2815 Q_{s,Yichang} - 8382 \ (r^2 = 0.8716) \quad (3)$$

If the left side of the equation is assumed equal to 0, and the equation is solved, the solution gives $Q_{s,Yichang} = 29\,800 \times 10^4$t/year $\approx 3 \times 10^8$t/year. This can be regarded as the threshold annual suspended load at Yichang station, at which the Yichang–Hankou# river reach may reach a non-fill, non-scour state.

Apart from mean annual river flow and suspended load, flood discharge also plays a role in determining sediment deposition. The relationship between the annual amount of sediment deposition and annual maximum water discharge at Yichang station has

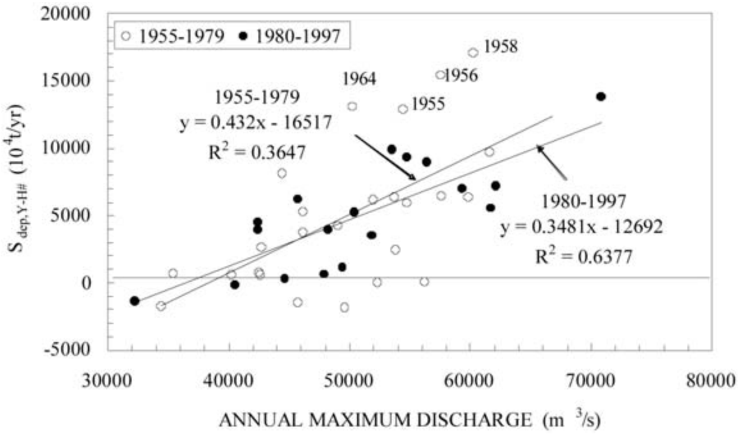

Fig. 7. Relationship between the annual amount of sediment deposition ($S_{dep,Y-H\#}$) and annual maximum water discharge at Yichang station

been plotted in Fig. 7, which shows a close positive correlation. The squared correlation coefficient is $r^2=0.43$, significant at a level of <0.01. When the points from the periods 1955–1979 and 1980–1997 are distinguished by different symbols, it can be seen that the distribution of the points from the former period is rather scattered, with the squared correlation coefficient $r^2=0.36$; but for latter period, the distribution is much more concentrated, with the squared correlation coefficient $r^2=0.64$.

To establish the relationship between the annual amount of sediment deposition ($S_{dep,Y-H\#}$) in the studied river reach and river flow and sediment load, a correlation matrix and a multiple regression analysis has been performed. The variables of river flow and sediment load include annual river flow ($Q_{w,Yichang}$), annual suspended load ($Q_{s,Yichang}$) and annual maximum water discharge ($Q_{max,Yichang}$) and the ratio ($R_{w,div}$) of annual river flow diverted through the three outfalls to the annual river flow at Yichang station and the ratio ($R_{s,div}$) of annual suspended load diverted through the three outfalls to

Table 1. The correlation matrix among $S_{dep,Y-H\#}$ (in 10^4 t/year) and $Q_{w,Yichang}$ (in 10^8 m^3/year), $Q_{s,Yichang}$ (in 10^4 t/year), $Q_{max,Yichang}$ (m^3/s), $R_{w,div}$ and $R_{s,div}$ for 1955–1997 and two subperiods

	$Q_{w, Yichang}$	$Q_{s, Yichang}$	$R_{s,div}$	$R_{w,div}$	$Q_{max, Yichang}$	$S_{dep,Y-H\#}$
1955–1997						
$Q_{w, Yichang}$	1.00	0.70	0.38	0.40	0.49	0.46
$Q_{s,Yichang}$	0.70	1.00	0.46	0.53	0.71	0.74
$R_{s,div}$	0.38	0.46	1.00	0.97	0.33	0.40
$R_{w,div}$	0.40	0.53	0.97	1.00	0.33	0.45
$Q_{max, Yichang}$	0.49	0.71	0.33	0.33	1.00	0.66
$S_{dep,Y-H\#}$	0.46	0.74	0.40	0.45	0.66	1.00
1955–1979						
$Q_{w, Yichang}$	1.00	0.73	0.40	0.53	0.65	0.68
$Q_{s,Yichang}$	0.73	1.00	0.50	0.53	0.45	0.34
$R_{s,div}$	0.40	0.50	1.00	0.95	0.54	0.51
$R_{w,div}$	0.53	0.53	0.95	1.00	0.57	0.60
$Q_{max, Yichang}$	0.65	0.45	0.54	0.57	1.00	0.60
$S_{dep,Y-H\#}$	0.68	0.34	0.51	0.60	0.60	1.00
1980–1997						
$Q_{w, Yichang}$	1.00	0.76	0.75	0.82	0.57	0.73
$Q_{s,Yichang}$	0.76	1.00	0.89	0.86	0.81	0.93
$R_{s,div}$	0.75	0.89	1.00	0.97	0.68	0.86
$R_{w,div}$	0.82	0.86	0.97	1.00	0.66	0.86
$Q_{max, Yichang}$	0.57	0.81	0.68	0.66	1.00	0.80
$S_{dep,Y-H\#}$	0.73	0.93	0.86	0.86	0.80	1.00

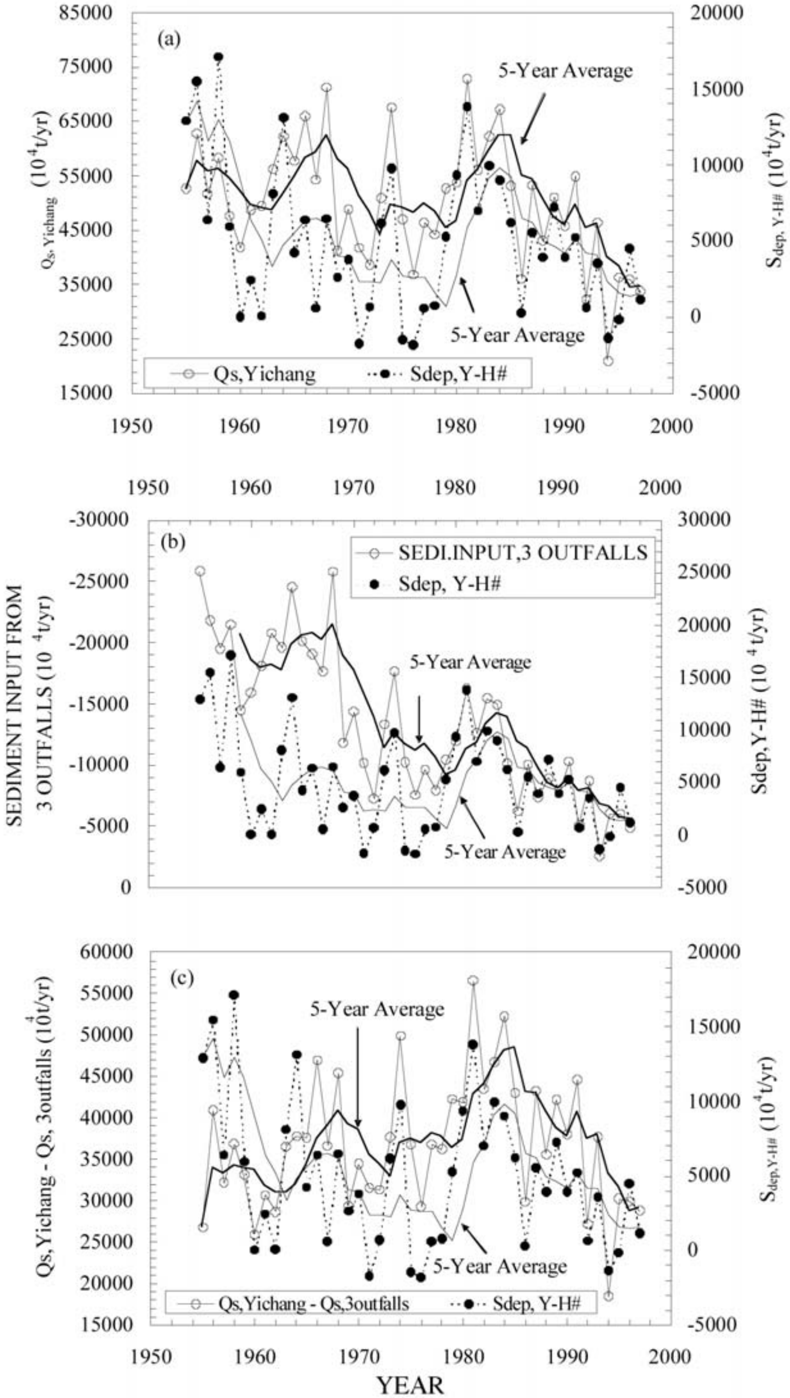

Fig. 8. Comparison of the temporal variations in the annual sediment deposition amount ($S_{dep,Y\text{-}H\#}$) of the studied river reach and the suspended load at Yichang station (a), in $S_{dep,Y\text{-}H\#}$ and the sediment inflow ($Q_{s,3outfalls}$) through the three outfalls (b), and in $S_{dep,Yichang}$ and the index ($Q_{si,Yichang} - Q_{s,3outfalls}$) (c)

Table 2. Results of multiple regression (R is multiple correlation coefficient, F is the result of the F-test, p is the probability of significance, and SE is the standard error of estimate)

Period	Multiple regression equation	R	F	p	SE
1955–1997	$S_{dep,Y\text{-}H} = -11966 - 1.179Q_{w,Yichang} + 0.2256Q_{s,Yichang} - 9983R_{s,div} + 20271R_{w,div} + 0.1772Q_{max,Yichang}$	0.772	10.91	1.68×10^{-6}	3258
1955–1979	$S_{dep,Y\text{-}H} = -5553 - 5.952Q_{w,Yichang} + 0.4740Q_{s,Yichang} + 14300R_{s,div} + 16578R_{w,div} + 0.05806Q_{max,Yichang}$	0.808	7.14	0.00065	3569
1980–1997	$S_{dep,Y\text{-}H} = -4341 - 1.846Q_{w,Yichang} + 0.2548Q_{s,Yichang} - 86499R_{s,div} + 119891R_{w,div} + 0.04350Q_{max,Yichang}$	0.952	22.97	9.25×10^{-6}	1473

the annual suspended load at Yichang station. The multiple regression equations are established for the period 1955–1997 in general, and for the subperiods of 1955–1979 and 1980–1997 in particular. As pointed out earlier, the channel conditions for the periods 1955–1979 and 1980–1997 are different. In the former period, strong adjustment was underway following the three bend neck-cutoffs that occurred in 1967, 1968 and 1972. As can be seen from Fig. 5, after 1980, $S_{dep,Y\text{-}H\#}$ showed a clear decreasing trend. Therefore, multiple regressions were established for this subperiod.

The correlation matrix among $S_{dep,Y\text{-}H\#}$ and all the influencing variables has been calculated for the period 1955–1997, and the subperiods of 1955–1979 and 1980–1997 (Table 1). The multiple regression equations have been established for the period 1955–1997, and the subperiods of 1955–1979 and 1980–1997, respectively (see Table 2).

Comparison of the effects of the sediment load from upper Yangtze River and the sediment outflow through the 'three outfalls' on the sediment deposition in the studied river reach

Figure 8a shows that the variations in $Q_{s,Yichang}$ and in $S_{dep,Y\text{-}H\#}$ are synchronized, especially the trends of the five-year moving average. The trends of the five-year moving averages of $Q_{s,3outfalls}$ and $S_{dep,Y\text{-}H\#}$ have reverse phases, like a pair of mirror images. For a better comparison, the $S_{dep,Y\text{-}H\#}$ has been converted to negative values, meaning sediment 'input' ($Q_{si,3outfalls}$) from the three outfalls. Then, the temporal variations in $S_{dep,Y\text{-}H\#}$ and $Q_{si,3outfalls}$ are shown in Fig. 8b, which indicates a synchronized trend. Figure 8c shows that for the period after 1970, the index ($Q_{s,Yichang} - Q_{s,3outfalls}$) varies synchronously with $S_{dep,Y\text{-}H\#}$, but for the period before 1970, such trends are very weak.

Although the variations in $Q_{s,Yichang}$ and in $S_{dep,Y\text{-}H\#}$ are synchronized (see Fig. 8a), the distance between the two five-year moving average curves varied with time. In 1961 the sediment deposition curve crosses the sediment inflow curve; afterwards the distance between the two curves increased till 1979, and then decreased. This means that, compared with the variation in $Q_{s,Yichang}$, $S_{dep,Y\text{-}H\#}$ decreased before 1979; and after 1979, $S_{dep,Y\text{-}H\#}$ increased. Figure 8b shows that the distance between the two five-year moving average curves was small from 1955 to 1961, but increased sharply till 1970, and then decreased. After 1985, the distance became very small. This means that, compared with the variation in the sediment outflow ($Q_{s,3outfalls}$) through distributaries, $S_{dep,Y\text{-}H\#}$ decreased before 1979, but after 1979 it increased. This fact provides some proof to assess the effect of bend cutoffs on sediment transport and deposition in the river channel. After the cutoffs, the gradient of the channel increased, which enhanced the river's sediment-carrying capability. As a result, the channel was deepened, and $S_{dep,Y\text{-}H\#}$ decreased. Furthermore, when the channel deepening had proceeded upstream to the entrance of the outfalls to reduce the sediment outflow to the distributaries, the sediment load in the main stem increased. This may increase $S_{dep,\ Y\text{-}H\#}$ compared with the variation in $Q_{s,Yichang.}$ However, the increased sediment deposition may raise the bed, and then $Q_{s,3outfalls}$ may increase again, which may in turn result in further variation in $S_{dep,Y\text{-}H\#}$, and makes the course of adjustment complicated. It can be seen from Fig. 8b that $Q_{s,3outfalls}$ declined sharply from 1968 to 1979. This fact may be regarded as a result of bend cutoffs that occurred in 1967, 1969 and 1972.

The correlation coefficient between $S_{dep,Y\text{-}H\#}$ and $Q_{s,\ Yichang}$ is 0.74, but the correlation coefficient between $S_{dep,\ Y\text{-}H\#}$ and sediment load 'input' ($Q_{si,\ 3outfalls}$) from the three outfalls is –0.40. Hence, the sediment load from the upstream drainage basin has a larger effect on the sediment deposition in the studied river reach than does the sediment diverted through the distributaries. To further determine the contribution of the two sediment factors on $S_{dep,Y\text{-}H\#}$, multiple regression equations have been estab-

Table 3. Regression equations between $S_{dep, Y\text{-}H\#}$ and $Q_{s, Yichang}$ and $Q_{si, 3outfalls}$, for the periods 1955–1997 and 1980–1997 (symbols are explained in text). N is the number of samples

Period	Multiple regression equation	N	R	F	SE	Contribution from $Q_{s,Yichang}$%	Contribution from $Q_{si,3outfalls}$%
1955–1997	(1) $S_{dep,Y\text{-}H} = -10008 + 0.2668Q_{s,} - 0.1228Q_{s,3outfalls}$	43	0.744	24.773	3294	79.90	20.10
	(2) $S_{dep,Y\text{-}H\#} = 0.6201Q_{s,Yichang} - 0.1560Q_{si, 3outfalls}$						
1980–1997	(1) $S_{dep,Y\text{-}H} = -6324 + 0.1465Q_{s,Yichang} - 0.4744Q_{si, 3outfalls}$	18	0.939	55.961	1472	51.43	48.57
	(2) $S_{dep,Y\text{-}H} = 0.4859Q_{s,Yichang} - 0.4590Q_{si, 3outfalls}$						

lished between $S_{dep,Y\text{-}H\#}$ and $Q_{s,Yichang}$ and $Q_{si,3outfalls}$ for the periods 1955–1997 and 1980–1997, and for the original data and the data standardized to the range of (0,1) (Table 3). After the data standardization the regression coefficients can be used to reflect the contribution of the two influencing variables to $S_{dep,Y\text{-}H\#}$. Assuming that the contributions of the influencing variables are in proportion to the absolute values of the regression coefficient and letting the total variation in $S_{dep,Y\text{-}H\#}$ be 1.0, the contributions of $Q_{s,Yichang}$ and $Q_{si,3outfalls}$ to $S_{dep,Y\text{-}H\#}$ can be estimated. It can be seen from Table 3 that, for the period 1955–1979, the relative contributions of $Q_{s,Yichang}$ and $Q_{si,3outfalls}$ to the variation in $S_{dep,Y\text{-}H\#}$ are 79.90% and 20.10% respectively; for the period 1980–1997, the relative contributions of $Q_{s,Yichang}$ and $Q_{s,3outfalls}$ to the variation in $S_{dep,Y\text{-}H\#}$ are 51.43% and 48.54% respectively. The difference between the two series is significant; in the period 1980–1997, the relative contribution of $Q_{si,3outfalls}$ became much larger.

Conclusions

The use of channel sediment budget opens a way to obtain data for the study of river response to environmental changes. The amount of sediment deposition at river-reach scales can be calculated using data of sediment loads collected from hydrometric stations controlling the flow and sediment input and output of the given river reach.

The sediment deposition amount of the Yichang–Wuhan reach has been determined using the concept of sediment budget at channel-reach scale, based on which the fill–scour process of the middle Yangtze River has been studied in response to the sediment load and flow inputs. The results show that the studied river reach has a function of ‘more input, more output’, and that on average, 13.3% of the net input sediment is deposited in the studied river reach. Since 1956, the output sediment load of the studied reach increased with time to 1981, followed by a decline. The increase in output before 1981 can be related to the man-made bend neck-cutoff which caused a decrease in the sediment load diverted through the three outfalls and increased the sediment-carrying capacity of the river. Thereby, the river could transport more sediment to the outlet of the studied river reach. The decrease in the sediment load output after 1984 was directly due to the decreased sediment load at Yichang station. A regression equation between annual amount of sediment deposition in the Yichang–Hhankou river reach and annual suspended load at Yichang station has been established; for this the critical suspended sediment load at Yichang station was determined to be 3×10^8 t/year, at which value the Yichang-Hankou river reach might be in a non-fill, non-scour state.

Multiple regression equations have been established to assess the contributions of influencing factors to the variation in sediment deposition in the studied river reach.

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